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Research Article

Linking Users' Subjective QoE Evaluation to Signal Strength in an IEEE 802.11b/g Wireless LAN Environment

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Although the literature on Quality of Experience (QoE) has boomed over the last few years, only a limited number of studies have focused on the relation between objective technical parameters and subjective user-centric indicators of QoE. Building on an overview of the related literature, this paper introduces the use of a software monitoring tool as part of an interdisciplinary approach to QoE measurement. In the presented study, a panel of test users evaluated a mobile web-browsing application (i.e., Wapedia) on a PDA in an IEEE 802.11b/g Wireless LAN environment by rating a number of key QoE dimensions on the device immediately after usage. This subjective evaluation was linked to the signal strength, monitored during PDA usage at four different locations in the test environment. The aim of this study is to assess and model the relation between the subjective evaluation of QoE and the (objective) signal strength in order to achieve future QoE optimization.

1. Introduction

In today's mobile ICT environment, a plethora of innovations on the market are pushing the boundaries of what is technically feasible and offering new technologies and access networks to end-users. It is often assumed that the growth and optimization on the supply side will automatically result in their swift adoption on the consumption side. In this respect, however, numerous examples of failing innovations seem to confirm the observation that end-users nowadays display a greater selectivity and a more critical attitude in their adoption and appropriation behavior. It is believed that new applications and services are increasingly evaluated by users in terms of Quality of Experience (QoE). Moreover, it is assumed that applications or services that meet users' requirements and expectations and that allow them to have a high QoE in their personal context will probably be more successful (e.g., in terms of adoption) than applications or services that fail to meet users' high demands and expectations. As a result, the importance of a far-reaching insight into the expectations and requirements,

as well as into the actual quality of users' experiences with mobile applications, is widely acknowledged. To date, however, it is still largely unknown how the objective and subjective counterparts of these experiences can be measured and linked to each other in order to achieve further optimization.

In this paper, we therefore focus on the crucial, but often overlooked, relation between technical quality parameters and subjective indicators of QoE. Indeed, in line with [1], QoE is conceived as a multidimensional concept that consists of both objective (e.g., network-related parameters) and subjective (e.g., contextual, user-related) aspects. In this respect, the paper presents a software tool that is embedded in an interdisciplinary approach for QoE measurement and that enables us not only to assess the subjective evaluation of QoE by end-users and to monitor Quality of Service- (QoS-) related aspects of mobile applications, but also to model their relation in order to achieve the optimization of QoE. As an illustration, this paper shares results from an empirical study in which a mobile web-browsing application (Wapedia) was tested on a Personal Digital Assistant (PDA)

and evaluated in terms of QoE by a user panel in an indoor IEEE 802.11b/g Wireless LAN environment. By means of a short questionnaire presented to the users on the device, a number of key QoE dimensions were evaluated. This subjective evaluation was then linked to the signal strength, whose usage was monitored by means of the above-mentioned software tool at four different locations in the test environment. The aim of this study is to assess and model the relation between the subjective QoE (as evaluated by the test users) and signal strength in order to gain more insight into the interplay between these components of QoE, information that is crucial for its optimization.

The remainder of this paper is organized as follows. Section 2 deals with related work from the literature, while Section 3 expands on the proposed interdisciplinary approach for user-centric QoE measurement and the software tool for determining the relation between objective and subjective QoE dimensions. Details about the study setup are discussed in Section 4, followed by an overview and discussion of the results in Section 5. Finally, Section 6 is dedicated to our conclusions and suggestions for future research on QoE in mobile living lab environments.

2. Related Work

2.1. Definition and Dimensions of Quality of Experience. A review of the relevant literature shows that most definitions and empirical studies of QoE tend to stay close to the technology-centric logic and disregard the subjective character of user experiences [2, 3]. It is rather uncommon to integrate concepts from other fields less technical than telecommunications in definitions of QoE. A relevant example is the domain of “Human-Computer Interaction,” in which concepts such as “User Experience” and “Usability” closely related to QoE are very important [4].

Often, narrow, technology-centric interpretations of QoE go hand in hand with the assumption that by optimizing the QoS, the end-user’s QoE will also increase. However, this is not always the case: even with excellent QoS, QoE can be really poor [5]. There are several examples of studies where QoE is interpreted in such a narrow way. For example, in [2], the QoS of the network is seen as the main determinant of QoE. In [3], QoE is defined as the “general service application performance,” consisting of properties (such as service accessibility, availability, and integrity) that are measured during service consumption. In yet another study [6], QoE is determined by looking at the video quality within a video-conferencing system.

In this paper, however, QoE is approached from a broader interdisciplinary perspective. It is seen as a multidimensional concept that consists of five main building blocks. The identification of these building blocks and their integration into a more comprehensive model of QoE are based on a thorough literature review and a consultation with international experts on QoE, QoS and User Experience. This model does not only take into account how the technology performs in terms of QoS, but also what people can do with the technology, what they expect from it, in what context people

use it/intend to use it, and to what degree it meets their expectations [7]. It represents a classification of the wide range of aspects and metrics that may influence the quality of a user’s experience when using a certain application or service. These five building blocks, which are shown in Figure 1, are as follows [7].

- (i) *Quality of Effectiveness.* It deals with technical performance (at the level of the network, infrastructure, application, and device). This building block represents the traditional QoS parameters, which represent a crucial component of QoE.
- (ii) *Quality of Efficiency.* It determined by the way technical performances are appreciated by the user, thus requiring a subjective evaluation.
- (iii) *Usability.* It deals with how easy it is for the user to accomplish tasks.
- (iv) *Expectations.* The quality of users’ experiences (good or bad) is influenced by the degree to which users’ expectations “*ex ante*” are met.
- (v) *Context.* It deals with the various contextual aspects that might influence a user’s QoE (e.g., individual context, social context, etc.).

The empirical study presented in this paper draws on this conceptual definition of QoE. Similar to this conceptualization, both technical and nontechnical dimensions are identified in [8]. This approach distinguishes between measurable and nonmeasurable metrics.

In Section 3, we demonstrate the way in which the identified building blocks were integrated into our approach and how the selected QoE dimensions were measured. In the next section, we discuss some of the current approaches for QoE measurement.

2.2. Measuring QoE. The literature on QoE measurement usually draws a distinction between objective and subjective assessment methods. These aim to evaluate that “perceived QoEs” from a user perspective are not automated and involve real users to some degree. As a result, they are usually considered as too time-consuming and too expensive [9]. Although one could expect “subjective methods” to allow researchers to gain a deeper understanding of the subjective dimensions of QoE (see Section 2.1), this seems to be a misconception. The use of Mean Opinion Scores (MOSs) as a subjective performance measure is rather common in QoE measurement. Although MOS testing has a “subjective measure” label, it draws on the conversion of objective quantities into subjective scores [10, 11]. It is an approach that is used for the evaluation of quality parameters by users and by means of standardized scales (with labels such as Excellent, Good, Fair, Poor, Bad [12]). For a number of reasons, the use of MOS testing has been criticized and extended to other “subjective” measures such as acceptability measures and (semi-) automated subjective measures such as the Pseudosubjective Quality Assessment (PSQA) [11, 13].

Perceptual objective test methods such as Perceptual Evaluation of Speech Quality (PESQ) [14, 15] and Perceptual

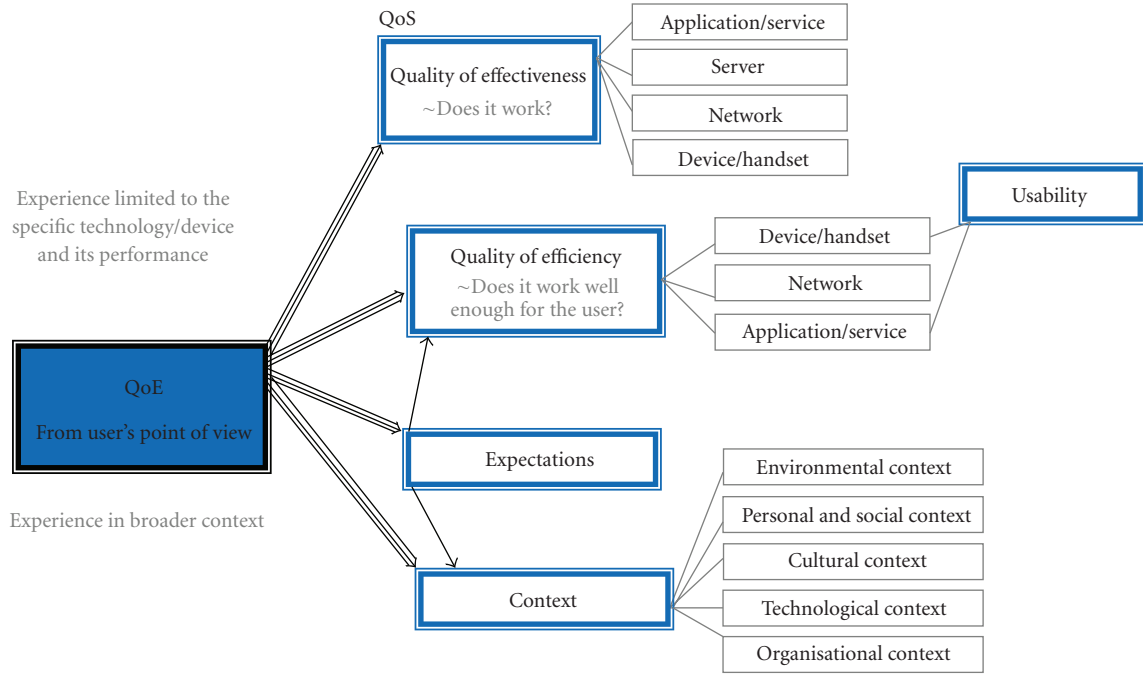


FIGURE 1: Conceptual model of QoE [7].

Evaluation of Video Quality (PEVQ) [16, 17] can also be mentioned in this context. Both are objective, automated assessment methods that involve perceptual models of human behavior. They are based on real subjective tests and enable researchers to assess speech and video quality, respectively, as experienced by users.

Whereas the MOS concept is mainly used in the voice domain as a subjective measure of voice quality, similar concepts have been developed to measure performance aspects of web-browsing in a user-centric way (i.e., the concept of dataMOS) [10]. Although this study and others [18] have tried to relate technical parameters to the (somewhat ambiguous) concept of “perceived QoE,” these approaches have been criticized from a more user-oriented perspective for various reasons, for example, undervaluation of the subjective character of QoE, little attention to the influence of contextual variables, only one research context, and so forth.

However, an increasing number of studies have tried to go beyond the limitations of “single-context” research environments. Ponce de Leon et al. [19] studied QoE in a distributed mobile network testbed environment drawing on the living lab approach. Perkis et al. [8] discuss a framework for measuring the QoE of multimedia services, while Li-yuan et al. [18] describe a new approach for evaluating QoE in a pervasive computing environment. In the context of measuring QoE in natural settings, some existing solutions such as the mobile QoS agent (MQA), which can be used for the measurement of service quality on cellular mobile terminals, can be mentioned [3]. Although these solutions for collecting data regarding the “What?” dimension of QoE in the context of mobile and wireless network usage are very valuable, they do not allow us to gain insights into the more subjective (e.g., “Why?” “Where?” “With whom?”)

dimensions of QoE that were identified in Section 2.1. We believe that the combination of state-of-the-art technical measures and user-oriented measurement techniques might offer important opportunities in this respect. This also implies that the evaluation of QoE should be embedded in an interdisciplinary approach, in which the traditional testbed setting is extended to a more user-centric, flexible, and multicontext research environment. In this respect, it is relevant to mention the open-source MyExperience tool [20] for supporting computerized in situ data collection that draws on experience sampling (self-reports) in natural settings. Once implemented on a mobile device, this device becomes a data collection instrument. A similar approach underlies this study.

3. An Interdisciplinary QoE Measurement Approach

3.1. Five-Step Interdisciplinary Approach for User-Centric QoE Measurement. As mentioned above, the use of the software tool presented in this paper is embedded in an interdisciplinary approach for user-centric QoE measurement. In this context, “interdisciplinary” refers to our multidimensional conceptualization of QoE. It implies that for the evaluation of the five distinct dimensions identified in Section 2.1, a more holistic and integrated approach is required. As a result, our proposed approach combines knowledge and tools from different disciplines in order to link user-centric QoE evaluation measures to technical (QoS-related) QoE parameters and to model the relation between the former and the latter. This interdisciplinary methodology consists of the following steps.

- (1) *Preusage user research* based on a combination of qualitative and quantitative methods; that is, to detect the “most relevant QoE dimensions and users” expectations based on a tailored concretization of the conceptual model described in Section 2.1.
- (2) *Preusage translation* workshops to find an optimal match between user-indicated QoE dimensions and measurable and objective QoE parameters. This step intends to bridge the gap between the social/user perspective and the technical perspective.
- (3) *Monitoring of QoS parameters during usage*: this step includes the actual usage of the selected application or service by the test users. In order to collect the relevant data, a software probe model that measures data across different QoE dimensions was developed. This software tool is described in detail in Section 3.2.
- (4) *Postusage questions on device* (e.g., PDA): during this step, respondents receive a number of questions on the device asking them to evaluate the quality of their experience by rating a number of relevant QoE dimensions (based on the conceptual model and the outcome of step (1)).
- (5) *Postusage comparison of expectations versus the quality of the experience* in order to identify and explain differences/matches between expectations and actual experiences (based on information gathered in step (3) and further user research).

This paper will restrict itself to focus mainly on the monitoring of QoS parameters during usage (step (3)). In the discussion of the study setup (Section 4), we also elaborate on the postusage questions on the device (step (4)) that served as an evaluation of QoE by the test users.

3.2. Software Monitoring Tool. The idea of the monitoring tool is proposed in [21, 22]. The QoE engine is the core system that coordinates all the actions involved in QoE monitoring and assessment. It facilitates the measurement of QoE as a multidimensional concept that is built according to a probe model and distributed across end-user devices and the network. In order to collect the relevant information, this probe model measures data across the different building blocks that might influence users’ QoE (see Section 2.1). It is an insitu application [23] connected to back-end infrastructure that stores and analyzes the incoming data.

Our monitoring tool consists of three layers, with each one consisting of one or more software monitoring probes. These are modular components that can be inserted, enabled, or disabled within the QoE engine. The coordination of all these components is executed by means of a QoE processor. Each probe fulfills a specific task.

- (i) The **contextual probes** consist of software probes that deal with the determination of the context of the application usage. This can consist of GPS data (environmental context), information coming from the user’s agenda, or data reflecting the user’s current mood or activities.

- (ii) The **experience probes** consist of the software probes with built-in intelligence in order to capture the subjective character of users’ experiences. For example, automatic questionnaires can be sent to the user on the mobile device before, after, or even during application usage. Other examples include the detection of application usage by monitoring keystrokes, tracing events (such as video player activity based on system logs, changes in location, etc.), and the like.
- (iii) The **QoS probes** consist of the software probes that deal with the monitoring of the technical parameters such as network performance (e.g., throughput), device performance and capabilities (e.g., CPU power), and application properties (e.g., video codec).

Partitioning of the monitoring model in these three layers enables interdisciplinary *collaboration* among experts with different backgrounds such as social researchers, ICT researchers, and usability experts. Moreover, this modular approach of the QoE engine does not only enable easy monitoring of currently available parameters, but it can also be extended to new parameters (e.g., face recognition, contextual information, etc.). In view of this, additional modules can be created and inserted into each category of probes.

We now turn to a concrete study in which the above-mentioned tool was used for evaluating a mobile web-browsing application in terms of QoE. The proposed approach (including the use of the software tool) can also be applied to other applications and circumstances than the ones discussed in this paper.

4. Empirical Study Setup

4.1. Objectives. The aim of this study was to evaluate the QoE of a web-browsing application in a controlled wireless environment by combining implicit, objective data on signal strength (collected by the monitoring tool using a QoS probe) and explicit, subjective data (on selected QoE dimensions evaluated by test users using the experience probe). More specifically, we wanted to investigate and model the relation between these objective and subjective data in order to gain more insight into the interplay between these dimensions of QoE. The motivation for focusing on just one technical parameter here (i.e., signal strength) stems from the notion that QoE is a highly complex concept consisting of various parameters and dimensions. Given this complexity, it is necessary to gain a deeper understanding of these distinct parameters and dimensions before the relation between various technical parameters and subjective QoE dimensions can be modeled successfully. Moreover, in [24], linear regression models were given to predict QoE related to mobile multimedia. Based on the results in that study, block error rate (BER) appears more relevant than other quality metrics in the prediction of QoE. Therefore, we have chosen the signal strength as the first technical parameter to study because it obviously has a high correlation with BER in the case of wireless networks. Moreover, the delay also has a

high level of correlation with the signal strength because at the network layer level, the Transmission Control Protocol resends lost packages when low-signal strength situations occur as a result of high BERs.

We will now briefly discuss how we tried to attain the main aim of the study by successively describing the user panel, the application, the measurement approach and measurement equipment, the test environment and, finally, the evaluation procedure.

4.2. User Panel. As the current paper presents a concept that will be extended to larger-scale research in living lab environments, and as the setup of this kind of study is resource-intensive, the size of the user panel in this study was limited. The panel consisted of 10 test users (mean value $M = 35.1$ years, standard deviation $SD = 12.1$ years) who were recruited based on predefined selection criteria (i.e., sex, age, profession) by a specialized recruitment office. Although this way of working entails a significant cost, it allowed us to compose a diverse panel consisting of people with different profiles. The ages of the participants ranged from 19 to 51 years, and six of them were older than 30 years. Four test users were female, and six were male. The professions of the participants also varied: housewives, employees, workers, and students participated. The test users completed all five steps in the above-mentioned interdisciplinary approach: before and after the actual usage of the application, they were interviewed by a social scientist who inquired about their current experiences with mobile applications and their expectations and personal interpretation of a good/bad QoE. However, the results from this qualitative research are not discussed here.

4.3. Application: Wapedia. For the tests, we used a mobile web-browsing application, Wapedia, which is a mobile Wiki and search application. This application is similar to “Google Internet search,” but adapted for use on PDAs and Smartphones.

4.4. Measurement Approach and Measurement Equipment: PDA. In this study, the experience probe (see Section 3.2) was implemented as a questionnaire on the PDA. Using a QoS probe, the Received Signal Strength Indication (RSSI) was monitored. This RSSI is an indication (values ranging from 0 to 255 depending on the vendor) of the power present in a received radio signal and can be used to calculate the signal strength P [25]. A contextual probe was used to keep track of the locations where the tests took place. The final implementation of the client software was done in C# within the NET Compact Framework 2.0 and by using Windows Forms. Auxiliary classes were taken from the Smart Device Framework v2.1 from OpenNetCF [26]. This framework provided classes within which to retrieve the RSSI value for the received power, as measured by the available wireless network card. For the sake of reusability and extensibility, we used C# Reflection for the dynamic loading and unloading of additional monitoring probes. The back-end was programmed in Java using the Java Enterprise Edition

5 framework and the standard Sun Application server with a Derby database. The communication between the client and back-end was carried out using the SOAP (Service-Oriented Architecture Protocol) web services protocol. For the “mobile device,” we selected the HP IPAQ rw 6815. The PDA/Smartphone weighs 140 g and has a 2.7” screen with a color display. It incorporates GSM/GPRS/EDGE, WiFi (IEEE 802.11b/g), and Bluetooth. The device has 128 MB of storage memory and 64 MB of RAM. This high-end device thus enables access to the Internet on the move.

4.5. Test Environment: Indoor Wireless. The tests took place in an indoor Wi-Fi office environment (IEEE 802.11b/g), in which four different locations were selected. At every location, another usage scenario had to be executed. The floor plan (Figure 2) provides a better overview of the test environment and indicates the four locations (P1, P2, P3, P4). These locations were at different distances from the access point (type D-Link DI-624 wireless access point, red dot in the floor plan), corresponding with different measured signal strengths P . For example, location 1 was the closest to the access point resulting in the highest median signal strength.

4.6. Evaluation Procedure. The flow graph of Figure 3 summarizes the evaluation procedure and gives a schematic overview of the study setup components discussed above.

As already mentioned, this paper only focuses on steps (3) and (4) of the five-step approach described in Section 3.1. The participants were given a PDA and after a short briefing, they were asked to execute four usage scenarios using the Wapedia application at the four different locations. These locations and scenarios were selected at random for each user. Completing a single usage scenario took about 10 to 20 minutes. Different usage scenarios were proposed. For example, during a “holiday” in Paris, the participants had to find out where the Mona Lisa painting was located and retrieve some pictures of the museum, among other tasks. For each scenario, there were different usage contexts and topics (e.g., retrieving geographical information, looking up information on a music band, looking for a specific supermarket). By using different scenarios, the influence of repeated tests was minimized.

During the tests, the received signal strength, linked to the “Quality of Effectiveness” building block from Section 2.1, was monitored by means of the software tool described above. For the subjective evaluation of QoE by the test users, a set of questions related to a number of QoE dimensions selected from the conceptual model was integrated into a short questionnaire. After finishing a usage scenario, the users were asked to complete this questionnaire, which was automatically displayed on the PDA. It contained questions dealing with the expectations of the test users, their evaluation of the performance, the usability and use of the application, and their general experience. As these aspects were discussed in detail during the qualitative preusage interviews and during the briefing, the questionnaire itself was deliberately kept as short as possible in order to lower

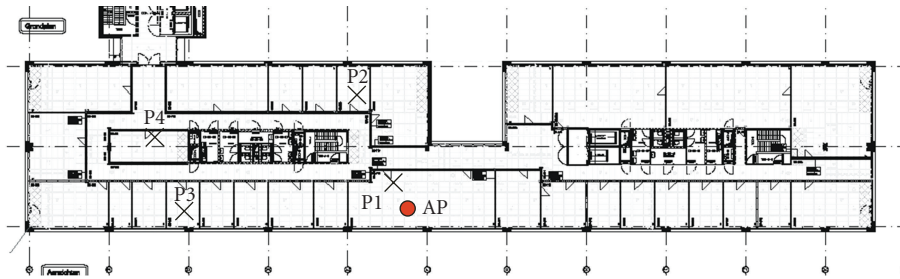


FIGURE 2: Floor plan of the test environment.

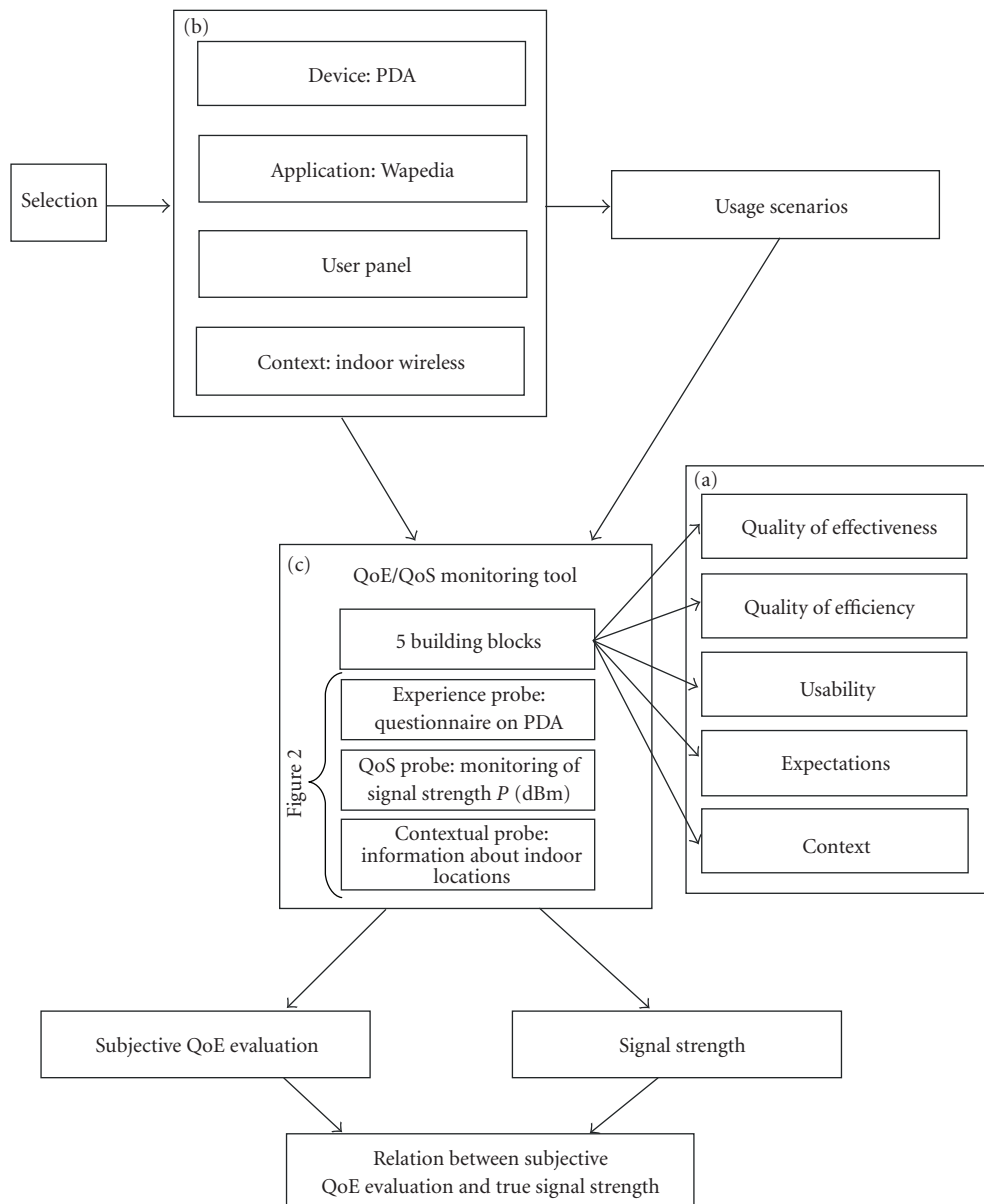


FIGURE 3: Flow graph of the following procedure.

the burden for the test users and in order to limit the level of interruption. The test users were asked to evaluate these QoE aspects by rating them on five-point Likert scales. The interpretation of these scores was explained in the briefing. The survey consisted of the following questions linked to a number of dimensions from the conceptual QoE building blocks identified in Section 2.1 (translated from Dutch).

- (i) Q1: Did the application meet your *expectations*? (linked to building block “Expectations” in the conceptual model.) In this respect, we can also refer to Roto [27], who stated that for mobile web-browsing experiences, the expectations of the users have to be taken into consideration as they might influence the QoE as evaluated by the users.
- (ii) Q2: Could you indicate whether or not you are satisfied about the *speed* of the application? (linked to building block “Quality of Effectiveness” in the conceptual model.)
- (iii) Q3: Could you indicate whether or not you found the application *easy to use*? (linked to building block “Usability” in the conceptual model.)
- (iv) Q4: Could you indicate whether or not you felt *frustrated* during the usage of the application? (linked to building block “Context” (personal context: feelings) in the conceptual model.)
- (v) Q5: After having tried the application, would you *reuse* it? (linked to building block “Context” (personal context) and building block “Expectations” [anticipation of behavior] in the conceptual model.)
- (vi) Q6: In general, how would you rate your *experience*? (linked to building block “Quality of Effectiveness” in conceptual model.)

As people tend to adjust and change their expectations of an object all the time based on both internal and external sources, these questions were asked after every scenario. Although the test users in this study were not aware of the fact that the different locations corresponded with different signal strengths, it could be interesting to investigate in future research whether the subjective evaluation of QoE differs significantly when users do receive information regarding technical parameters.

After completion of the questionnaire, the monitored signal strength and the responses were saved on the PDA and automatically transmitted to the server for further analysis. The 10 participants, thus, answered six questions at each of the four locations, resulting in 60 samples per location, or 40 samples per question, and a total of 240 samples. We now turn to the most important results of this study.

5. Results and Discussion

In this section, we first take a look at the field strengths in the different locations. Next, the evaluation of QoE dimensions by the test users is tackled. Finally, the relation between this subjective evaluation of QoE dimensions and the objective parameter of signal strength is assessed and modeled.

5.1. Technical Quality: Field Strength. A relatively constant signal strength (with unit decibel mW, noted as dBm, and calculated from the RSSI) for all the scenarios can be noticed. This is expected because the tests were performed in an indoor environment with little or no movement. The median values for the different locations 1–4 were equal to -43 dBm ($SD = 4.0$ dB), -61 dBm ($SD = 4.0$ dB), -79 dBm ($SD = 5.1$ dB), and -83 dBm ($SD = 4.4$ dB), respectively. The best reception conditions (QoS), that is, the highest signal strength, were measured at locations 1 and 2. Locations 3 and 4 had the worst signal quality. In an outdoor situation, the standard deviations would be much larger.

5.2. Evaluation of QoE Dimensions by the Test Users. First, the experience of a randomly selected user at the different locations is discussed. Next, differences among users are discussed, and a comparison between different users at different locations is made.

5.2.1. Results for a Specific User. As an illustration of the proposed approach (see Section 3.1), and because we believe that investigating the results of one or more specific participants in detail might help us to gain insight into the complex QoE concept, we first discuss the results of user 10 (male of 33 years old), who was randomly selected from the test panel. When we consider some results for user 10 from the research preceding the actual usage of the application (Section 3.1, step (1)), we record that this user displayed high expectations with respect to the availability and speed of the network and the response time at the application level. Moreover, these aspects were rated as very important by user 10. Steps (3) and (4) included *monitoring during usage* and *postusage question on the device*, respectively. Figure 4 shows user 10's ratings for all questions (Q1 to Q6) as a function of the median signal strength P in dBm at the different indoor locations (see Section 5.1). The ratings indicate that user 10 shows great satisfaction up to -79 dBm, with ratings of 5 for expectations, reuse, and general experience. At -79 dBm, a slight reduction in speed is noticed by this user due to the much lower signal strength; more time is needed to load pictures, for example, onto the PDA and, as a result, the application appears to be slower. The ratings for speed and general experience drop significantly at -83 dBm (rating 1). Expectations and reuse remain relatively high for user 10, and despite the bad experience at -83 dBm, he would still reuse this application. When we look at the level of frustration (Q4), we notice that user 10 did not feel frustrated at locations 1 and 2 (-43 and -61 dBm, resp.). At location 3 (-79 dBm), user 10 already notices the decreased speed due to the lower signal strength. At -83 dBm, he is slightly more frustrated due to the very low speed. During the postusage user research (step (5)), it became clear that respondent 10 was not very satisfied with the above-mentioned QoE subdimensions, and given the importance attached to these aspects, this resulted in an experience gap for user 10. This example illustrates how the proposed approach allows us to gain insight into the user's subjective evaluation of QoE by looking at what is happening at the technical level.

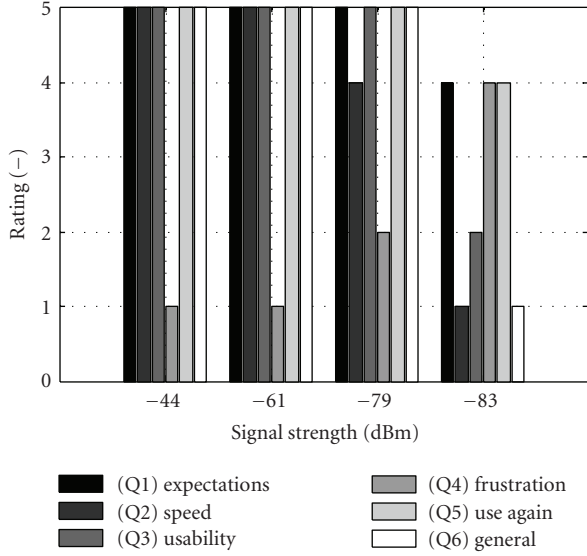


FIGURE 4: Ratings of the questionnaire (Q1, Q2, Q3, Q4, Q5, Q6) as a function of the signal strength for user 10.

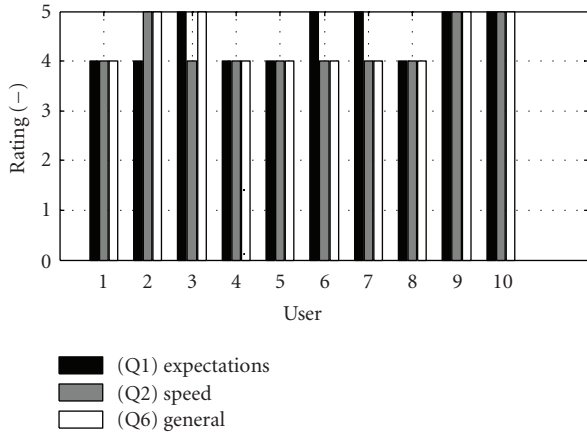


FIGURE 5: Actual ratings of the questionnaire (Q1, Q2, and Q6) for all users at location 2 (high signal strength).

5.2.2. Results for All Users at Different Locations. Figure 5 shows the actual ratings for expectations (Q1), speed (Q2), and general experience (Q6) for location 2, where a high median signal strength of -61 dBm is monitored. The ratings at this location are very high: average ratings of 4.5, 4.3, and 4.4 are obtained for questions Q1, Q2, and Q6, respectively (see also Table 1, Section 5.3).

The ratings for the same questions at location 4 (median $P = -83$ dBm) are depicted in Figure 6. The ratings at location 4 are considerably lower than at location 2; the average ratings here are 3.8, 2.3, and 3.1 for questions Q1, Q2, and Q6, respectively (see Table 1, Section 5.3). Users 1, 5, and 10 give ratings of 1 compared to ratings of 4 or 5 at location 2.

This shows that a relation may exist between the subjective QoE evaluation by the test users and the signal strength (see Section 5.3). But one has to be careful: despite

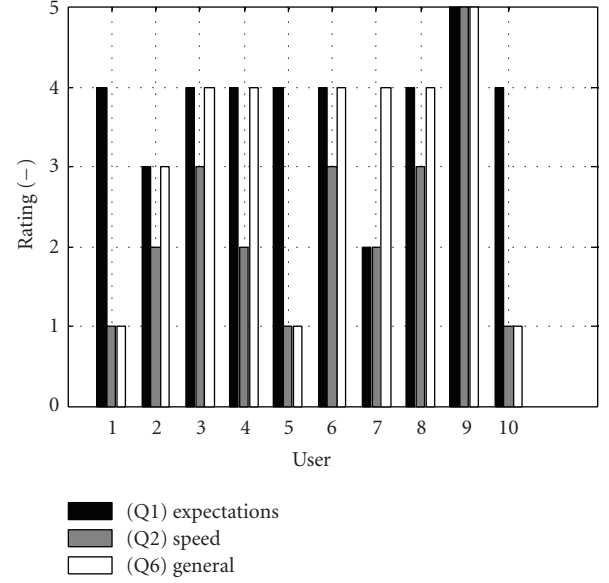


FIGURE 6: Ratings of the questionnaire (Q1, Q2, and Q6) for all users at location 4 (very low signal strength).

the low signal quality at location 4, users 3, 6, and 8 still had a reasonable-to-good experience, while user 9 was very satisfied (ratings of 5 for each question). User 9 is a housewife who is 43 years old with three children, and she mentioned in the preusage interview that she was not familiar with advanced mobile applications, so she was excited about the possibilities of the application on the PDA, even when the application worked very slowly.

In Figures 7 and 6, we compare the levels of frustration for all users at location 2 ($P = -61$ dBm) and at location 4 ($P = -83$ dBm). Again, the lowest level of frustration is found at location 2; all frustration ratings are lower or equal to the ratings at location 4, where the level of frustration is much higher in general. But despite the low speed and low signal strength, users 6 and 7 have the same low levels of frustration for both locations; users 6 and 7 also had a somewhat higher median signal strength of -80 dBm. User 9 also gave a rating of 2 as his level of frustration for location 4. In general, though, the frustration increases for all users when the signal strength is lower.

5.3. Relation between QoE as Subjectively Evaluated by the Test Users and the Objective Parameter of Signal Strength: Models and Discussion. In Table 1, the average ratings (M), standard deviations (SD), and correlation coefficients for the ratings of Q1–Q6 at locations 1–4 are presented. The average ratings of Q2, Q4, and Q6 at locations with high median signal strength (locations 1 and 2) are considerably higher than at location 4 with very low signal strength.

The correlation coefficients ρ for speed (Q2), frustration (Q4), and general experience (Q6) are 0.40, -0.33 , and 0.31, respectively. These correlations are significant at $P < .05$. They are not very high because the questions of speed and general experience received low ratings only at the locations

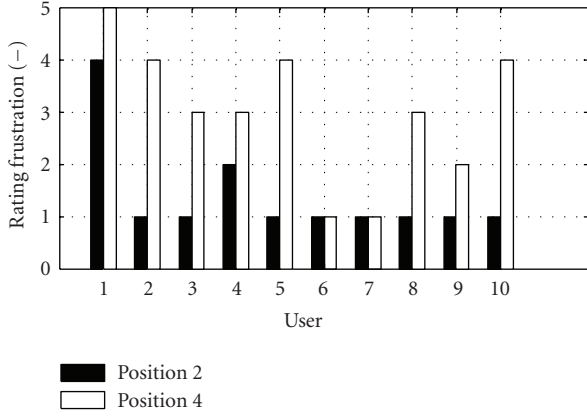


FIGURE 7: Comparison of ratings of frustration (Q4) for all users at location 2 ($P = -61$ dBm) and at location 4 ($P = -83$ dBm).

with very low signal strengths. Moreover, some people were relatively satisfied even when the signal strength was bad (see also Section 5.2.2). The correlations for Q1 (expectations), Q3 (usability), and reuse (Q5) are 0.18, 0.08, and 0.20 (with P -values much higher than .05), respectively, indicating that these aspects hardly depend upon signal strength.

We now investigate which questions depend upon signal strength. Therefore, we performed an *analysis of variance* (ANOVA), which tests the null hypothesis that the average ratings at the different locations are equal:

$$M_{Qx, \text{pos1}} = M_{Qx, \text{pos2}} = M_{Qx, \text{pos3}} = M_{Qx, \text{pos4}}, \quad (1)$$

where M is the average value of the rating of Qx (Question x ; $x = 1, 2, \dots, 6$) and $\text{pos } y$ is the y position ($y = 1, \dots, 4$). This analysis thus tests if the average ratings for the questions in Table 1 depend significantly on the position or median signal strength P .

Prior to performing the analysis of variance, various assumptions about the samples of the ratings have to be checked. Firstly, we assume that ratings for a question at the different positions are independent. This is realized by defining different scenarios for the users and by randomly assigning a location and a scenario to each user in successive experiments (randomization) (see Section 4.6). Therefore, it is assumed that the ratings for a question at the different positions are independent due to experimental design. We realize that users may be influenced by the previous expectations or multiple uses of the Wapedia application, but these aspects were also taken into account in the qualitative research and in the briefing before the actual usage.

Secondly, a Kolmogorov-Smirnov (K-S) test for normality was carried out on the ratings for Q1–Q6 at the different positions. All executed K-S tests passed at a significance level of 5%. Thirdly, Levene’s test was applied to the ratings for Q1–Q6 at the different positions to check homogeneity of variances (i.e., square of SD for rating of Qx is equal for all positions, $x = 1, \dots, 6$, see Table 1). For all combinations of the ratings at the different distances, Levene’s test passed at a significance level of 5%, so the

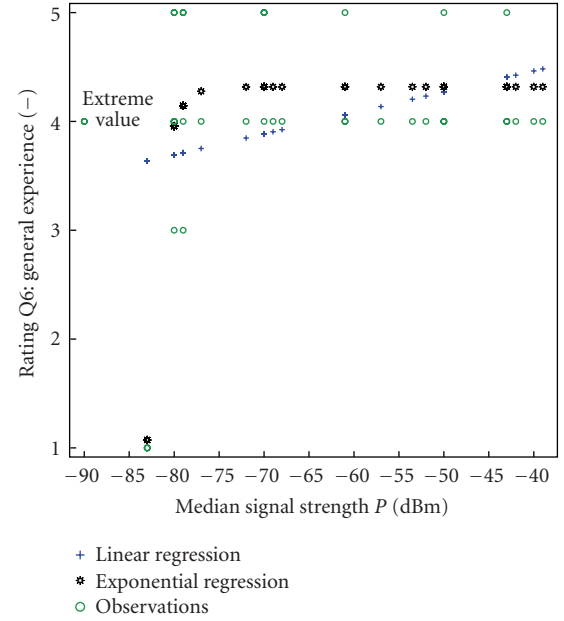


FIGURE 8: Rating of general experience (Q6) as a function of the monitored median signal strength and the regression fits.

assumption of homoscedasticity was met. In conclusion, all assumptions were found to be valid [28].

The analysis of variance shows that the null hypothesis of formula (1) was rejected for Q2 (speed), Q4 (frustration), and Q6 (general experience). For these specific cases, Tukey’s range test was then used for pair-wise comparison of $M_{Qx, \text{pos1}}$, $M_{Qx, \text{pos2}}$, $M_{Qx, \text{pos3}}$, $M_{Qx, \text{pos4}}$ ($x = 2, 4, 6$) at a simultaneous significance level of 5%. A significant difference in Q2, Q4, and Q6 was found between positions 1 and 4, 2 and 4, and 3 and 4, demonstrating that for these questions, the average ratings differ significantly for the different positions. Table 1 summarizes the results. For these ratings, regression analysis is also provided. For Q1 (expectations), Q3 (usability), and Q5 (reuse), the null hypothesis was not rejected, showing that these aspects of QoE do not depend on the different signal strengths. This was expected from Section 5.2.2, for example, for Q5, the reuse of an application will depend more upon the personal interests of the participant than on the available signal strength and, thus, speed.

Both linear and exponential regression models were applied to the data set. In the literature, we found that in case of real-time communication (such as voice and video communication), exponential regression (IQX hypothesis) [29] might be most suitable. When studying “traditional” web-browsing experiences, however, logarithmic regression [30] is proposed. Figure 8 shows the general experience as a function of the monitored signal strength for all users at all locations with both regression fits.

The observation (at -90 dBm, experience rating of 4) is treated as an extreme value and excluded from the analyzed data set. It was given by user 9 (see also Section 5.2.2), who was not familiar with advanced mobile applications and completely fascinated by the opportunity of mobile

TABLE 1: Average ratings and standard deviations for ratings of different locations by all users.

Question	Quantity	Average rating M and SD at different locations [–] location				Correlation coefficient
		1	2	3	4	
Q1: expectations	M	4.3	4.5	4.2	3.8	0.18
	SD	0.48	0.53	0.63	0.79	$P = .27$
Q2: speed	M	4.2	4.3	3.6	2.3	0.40
	SD	0.79	0.48	1.35	1.25	$P = .01$
Q3: usability	M	4.1	4.0	4.1	3.4	0.08
	SD	0.88	0.67	0.87	1.08	$P = .61$
Q4: level of frustration	M	1.9	1.4	2.6	3.0	–0.33
	SD	1.29	0.97	1.08	1.33	$P = .03$
Q5: reuse	M	4.0	3.9	4.2	4.0	–0.20
	SD	0.94	1.10	0.92	0.82	$P = 0.17$
Q6: general experience	M	4.2	4.4	4.2	3.1	0.31
	SD	0.42	0.52	0.63	1.52	$P = .03$

TABLE 2: Exponential regression models for rating Q2, Q4, and Q6.

$R^2 = 1 - (\text{Residual Sum of Squares}) / (\text{Corrected Sum of Squares})$	Exponential formula
$R^2 = 0.36$	Rating Q2 = $3.90 - 2.26 * \exp(-0.94 * P - 52.55)$
$R^2 = 0.25$	Rating Q4 = $1.93 + 2.66E - 26 * \exp(-0.72 * P - 0.01)$
$R^2 = 0.74$	Rating Q6 = $4.26 - 3.18E - 19 * \exp(-1.08 * P - 45.99)$

TABLE 3: Linear regression models for rating Q2, Q4, and Q6.

R^2	Linear formula
$R^2 = 0.16$	Rating Q2 = $0.03 * P + 5.76$
$R^2 = 0.11$	Rating Q4 = $-0.03 * P + 0.37$
$R^2 = 0.07$	Rating Q6 = $0.02 * P + 5.1$

web-browsing and who consistently gave high scores for all of the different network conditions. The accuracy of the exponential regression fit is larger by one order of magnitude than the linear regression fit (data in Tables 2 and 3).

The exponential regression fits shown in Table 2 were obtained for Q2 (speed), Q4 (frustration), and Q6 (general experience) as a function of the monitored median signal strength P (using least-squares fit).

The linear regression fits shown in Table 3 were obtained for Q2 (speed), Q4 (frustration), and Q6 (general experience) as a function of the monitored median signal strength P (using least-squares fit).

The slope for the ratings of Q2 and Q6 is positive and for the level of frustration (Q4) is negative (higher signal strength results in lower frustration).

Another approach is to build a regression tree model [31]. In this respect, Figure 9 shows a regression tree, which predicts the average ratings of general experience (Q6). The R^2 of the resulting regression tree is 48%. The entry point is at the top of the tree and the deviation is in a top-down direction. The root is at -81.5 dBm; in case of a lower signal strength of -81.5 dBm, the predicted average rating of Q6 is 2.2. This value can be found at the left side of the tree. In case of greater signal strength (e.g., -69.5 dBm) on the other

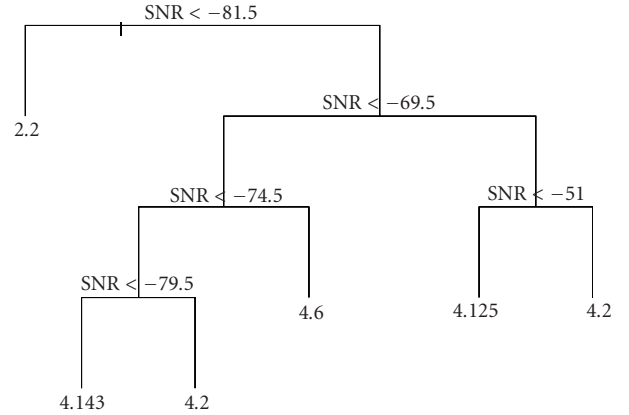


FIGURE 9: Regression tree of the monitored median signal strength. (The terminal nodes represent the average ratings of Q6.)

hand, the predicted average ratings are always higher than 4. These higher values are situated at the rightmost side of the tree. This type of analysis could be used as input for optimization purposes based on the predicted impact of specific QoE parameters on a user's experience.

It is, however, important to emphasize that these QoE models are only valid for the Wapedia application and in the described context of use. Our aim with these models is not to generalize the results that were obtained. Rather, we wanted to illustrate that there is a relation between the subjective evaluation of QoE and an objective technical parameter, in this case the signal strength, and that this relation can be modeled and expressed numerically. By doing this kind of research with large numbers of test users in

flexible, multicontext living lab research environments and with different types of applications, it may be possible to obtain more generally usable models that can be used for QoE optimization. Moreover, the proposed interdisciplinary approach might also help to gain more insight not only into the “What?” but also into the more user-centric aspects of QoE (i.e., “Why?” “Where?”, etc.)

6. Conclusion and Future Research

Although the literature on QoE has boomed over the last few years, most definitions and empirical studies of QoE tend to disregard the subjective character of the experience concept and hold onto a narrow QoS-related interpretation. As a result, few studies have focused on the relation between objective technical QoE parameters and subjective, user-centric indicators of QoE from a more holistic and interdisciplinary perspective. In this paper, QoE was therefore defined as a more holistic concept. Five main building blocks that may influence the quality of a user’s experience when using a certain application or service were discussed.

Building on this conceptual definition of QoE and on an overview of the relevant literature, a five-step interdisciplinary approach for measuring QoE as a multidimensional concept and for relating objective technical parameters to subjective user-related dimensions was introduced. An essential part of this approach is the software monitoring tool that facilitates the measurement of QoE. This tool is built according to a probe model consisting of three layers and is distributed across end-user devices and the network. The modularity of the software tool implies that it can easily be extended to new parameters. As a result, it offers many possibilities for the development of tailored or extended software tools for measuring the QoE of various types of mobile media.

In this paper, we discussed the use of this software tool in a study in which a panel of test users evaluated a mobile web-browsing application (Wapedia) on a PDA in an indoor IEEE 802.11b/g Wireless LAN environment. The aim was to assess and model the relation between the subjective evaluation of QoE and the signal strength. The test users were asked to execute four usage scenarios at four different locations. Immediately after completing a scenario, they were given a short questionnaire on the device (corresponding with QoE dimensions from the conceptual model). This subjective evaluation was linked to the signal strength, which was monitored during usage at the four different locations in the test environment.

It was shown that perceived speed, frustration, and general experience can be related to the available signal strength, for example, average ratings of 4.3~4.4 for perceived speed and general experience were obtained at a location with high signal strength, while the average ratings decreased to 2.3~3.1 at the location with very low signal strength. Significant correlations were obtained between perceived speed, frustration, general experience, and signal strength. A statistical analysis of variance showed that the average perceived speed, frustration and general experience depend

on the available signal strength. Different solutions for modeling the relation between the subjective QoE evaluation and signal strength were discussed.

The proposed approach and software tool offer opportunities for future large-scale research; user-centric QoE evaluation measures could be linked to a wider range of technical QoE parameters (e.g., delay, throughput, etc.) in a living lab environment in order to gain insight into and model the relation between users’ subjective QoE evaluations and technical parameters in different contexts. Combining these objective and subjective indicators of QoE thus offers important opportunities for complementing data on the “What?” dimension of QoE in the context of mobile and wireless network usage with knowledge of the more subjective dimensions of QoE. Future research will therefore focus on the evaluation of more user-, context-, device-, and network-related QoE dimensions. Moreover, in collaboration with social scientists, the tools for evaluating the subjective QoE dimensions can be further optimized.

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